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Desiccant cooling air conditioning: a review

K. Daou, R.Z. Wang*, Z.Z. Xia

School of Mechanical Engineering, Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University, Shanghai 200030, China

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Abstract

In this paper, the principles underlying the operation of desiccant cooling systems are recalled and their actual technological applications are discussed. Through a literature review, the feasibility of the desiccant cooling in different climates is proven and the advantages it can offer in terms energy and cost savings are underscored. Some commented examples are presented to illustrate how the desiccant cooling can be a perfective supplement to other cooling systems such as traditional vapour compression air conditioning system, the evaporative cooling, and the chilled-ceiling radiant cooling. It is notably shown that the desiccant materials, when associated with evaporative cooling or chilled-ceiling radiant cooling, can render them applicable under a diversity of climatic conditions.

Keywords: Technological applications; Desiccant wheel; Sensible heat ratio

Contents

* Corresponding author. Tel.: +86 21 62933838; fax: +86 21 62933250.
E-mail address: rzwang@sjtu.edu.cn (R.Z. Wang).

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Nomenclature

P	Vapour pressure [Pa]
C	Heat capacity rate [kW/K]
G	Mass flow rate per unit cross-sectional area [kg/m^2 s]
T	Temperature [K]
ε	Adsorption potential energy [J], Effectiveness
$\dot{m}_a$	Mass flow rate of process air [kg/s]
$\dot{m}_v$	Rate of water adsorbed from the processed air by the desiccant [g/s]
ξ	Concentration of desiccant solution [kg/m^3]
SHR	Sensible heat ratio
Subscript	
i	Inlet
o	Outlet
DW	Desiccant wheel
RHW	Rotary heat wheel
S	Desiccant Solution
wb	Wet bulb
c	Cooling medium
HE	Heat exchange
m	Moisture
a	Air
L	Liquid desiccant

1. Introduction

Air conditioning loads can be divided into two components, namely the sensible and the latent loads. An air conditioner must counterbalance the two sorts of load in order to maintain the desired indoor conditions. In order to remove the latent heat, the traditional refrigerant vapour compression system (VCS) or the not yet traditional vapour sorption system (VSS), cools the process air down below its dew point in order to condense out water vapour contained therein. The dehumidified air is then reheated to meet the required indoor temperature conditions. If the latent load is handled by other means than by this deep cooling, two components of the burden on the conditioner, brought about by the presence of latent load, will be avoided. Those are, namely, (1) the energy required to bring the air from the supply temperature down to the temperature of condensation of water vapour contained in the process air (below the dew point of the air), and (2) the energy needed to reheat the air from that temperature up to the supply air temperature. When the sensible heat ratio (SHR) of the conditioned space is low, the sum of these two components increases dramatically [1]. Furthermore the VCS are actuated by electricity, the generation of which involves most often the utilisation of fossil fuelled power plant with the consequent emissions of carbon dioxide (CO_2) into the atmosphere. Finally, the refrigerants used in this air conditioning technology are more or less CFCs based ones, that many countries are taking steps to phase out or are considering doing so.

The desiccant cooling can be either a perfective supplement to the traditional vapour compression air conditioning technology to attenuate the effects of its drawbacks, or an alternative to it for assuring more accessible, economical, and cleaner air conditioning. Still more importantly, when powered by free energy sources such as solar energy, and waste heat, it can significantly reduce the operating costs and increase considerably the accessibility to the air conditioning for the populations in remote areas, especially in developing countries.

The desiccants are natural or synthetic substances capable of absorbing or adsorbing water vapour due the difference of water vapour pressure between the surrounding air and the desiccant surface. They are encountered in both liquid and solid states. Each of liquid and solid desiccant systems has its own advantages and shortcomings. In addition of having lower regeneration temperature and flexibility in utilisation, liquid desiccant have lower pressure drop on air side. Solid desiccant are compact, less subject to corrosion and carryover. Commonly used desiccant materials include lithium chloride, triethylene glycol, silica gels, aluminium silicates (zeolites or molecular sieves), aluminium oxides, lithium bromide solution and lithium chloride solution with water, etc…

The desiccant materials are used in diverse technological arrangements. One of typical arrangements consists of using a slowly rotating wheel (8–10 revolutions/h) impregnated or coated with the desiccant, with part of it intercepting the incoming air stream while the rest of it is being regenerated.

Another arrangement uses the packing of solid desiccants to form a sort of adsorbent beds exposed to the incoming air stream, thus taking up its moisture. These beds need to be moved periodically in the direction of the regeneration air stream and then returned to the process air stream. Liquid desiccants are often sprayed into air streams or wetted onto contact surfaces to absorb water vapour from the incoming air. Like the solid desiccants,

they need to be afterwards regenerated in a regenerator where water vapour previously absorbed is evaporated out from it by heating. The desiccants can be coupled with the traditional air conditioning system to eliminate the overcooling and the reheat, thus downsizing the equipments and reducing their costs. Equally, they are used in conjunction with the chilled-ceiling panels to deal with the latent load. Their most frequent use remains, however, their employ with the evaporative cooling. Indeed, the evaporative cooling is the oldest technique of cooling. It has been superseded by the current more efficient and conveniently operated conventional air conditioning subsequent to the invention of this new technology. But the energy costs and the concerns related to environmental harms engendered by the refrigerants used in this system have prompted the researchers to begin looking back at the old cooling technique and trying to solve its main drawbacks. Those mainly boil down to the operating inefficiency in very humid climate, and even for the tropical and dry climate, their seasonal operating inefficiency (even in tropical climates, they become inefficient in rainy seasons). One of solutions is to dehumidifier the incoming air by forcing it through a desiccant so that the evaporative cooler can operate efficiently on a rather dry air stream.

This paper is intended to present a literature review of research works done by many researchers concerning various aspects of desiccant cooling technology in an effort to improve the efficiency of its applications.

2. Principles of desiccant cooling

Desiccant cooling consists in dehumidifying the incoming air stream by forcing it through a desiccant material and then drying the air to the desired indoor temperature. To make the system working continually, water vapour adsorbed/absorbed must be driven out of the desiccant material (regeneration) so that it can be dried enough to adsorb water vapour in the next cycle. This is done by heating the material desiccant to its temperature of regeneration which is dependent upon the nature of the desiccant used.

A desiccant cooling system, therefore, comprises principally three components, namely the regeneration heat source, the dehumidifier (desiccant material), and the cooling unit (Fig. 1).

The efficiency of desiccant system depends strongly on the Sensible heat Ratio (SHR). The SHR is defined as the ratio of the sensible heat gain to the sensible and latent heat gain of the space being conditioned. A low value of this quantity means that the total cooling load is predominately the latent load, in which situation desiccant cooling is demonstrated to be effective and economical.

The possible configurations and/or the composition of each of the three components can vary largely according to the nature of the desiccant employed as described in the following.

2.1. The desiccant dehumidifier

In the case where the desiccant is employed in its solid state, the desiccant dehumidifier is generally a slowly rotating desiccant wheel or a periodically regenerated adsorbent bed.

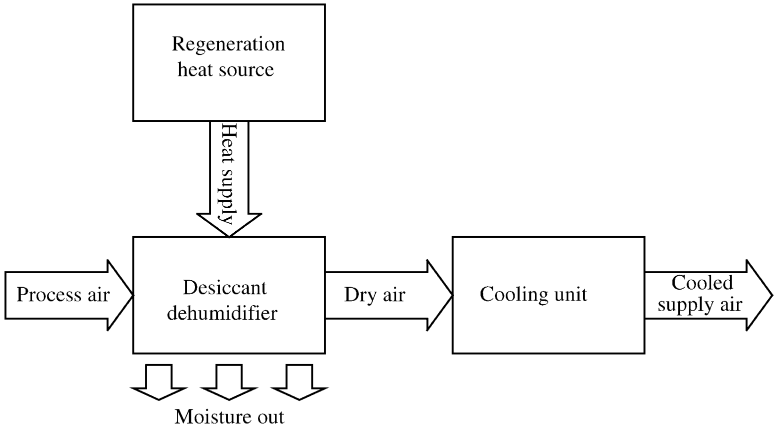


Fig. 1. Principle of desiccant cooling.

When the liquid desiccant is employed, the dehumidifier (absorber) is the equipment inside which the liquid desiccant is brought into contact with the process air stream. Its possible configurations include finned-tube surface, coil-type absorber, spray tower, and packed tower. The dehumidifier (absorber) and the regenerator are generally referred to as contactors. The packing mode of packed towers can be regular (structured) or random (irregular).

2.2. The cooling unit

The cooling unit can be the evaporator of a traditional air conditioner, an evaporative cooler or a cold coil. The role of the cooling unit is the handling of the sensible load while the desiccant removes the latent load. When a desiccant wheel system is implemented, a heat exchanger is generally used in tandem with it to preliminarily cool the dry and warm air stream before its further cooling by an evaporative cooler or a cold coil, etc. In this case, the heat exchanger together with the evaporator cooler or the cold coil constitutes the cooling unit. Fig. 2 shows in the form of psychrometric representation, the use of an evaporative cooler (state 3–state 4) and the cooling coil (state 3–state $4'$) in tandem with a heat exchanger cooler (state 2–state 3).

2.3. The regeneration heat source

The regeneration heat source supplies the thermal energy necessary for driving out the moisture that the desiccant had taken up during the sorption phase. Because the thermal energy source is required, a variety of possible energy sources can be utilised. Those include solar energy, waste heat, and natural gas heating, and the possibility of energy recovery within the system.

In the case of a liquid desiccant cooling being used, the heat of regeneration is furnished to the desiccant solution inside the structure of a regenerator where a scavenger air stream is concurrently blown to carry away the moisture desorbed under the heating.

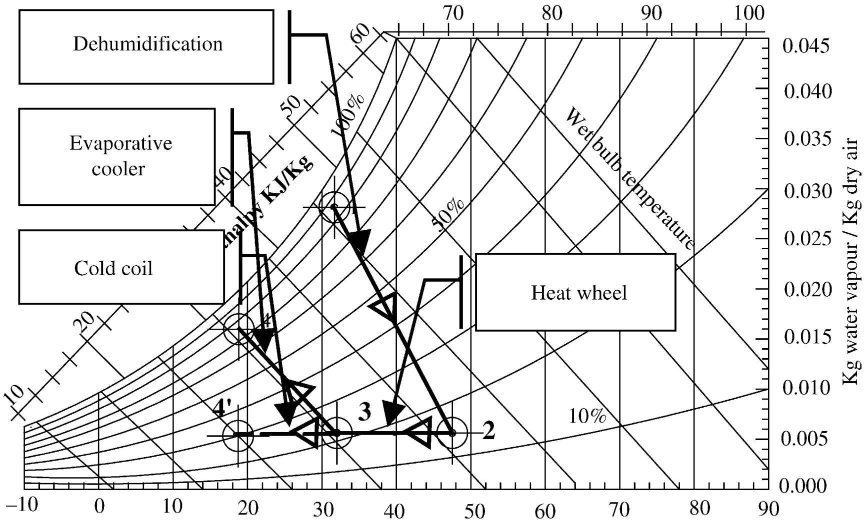


Fig. 2. Psychrometric chart illustrating the principle of desiccant cooling.

The scavenger air can also be a hot air stream brought into contact with the dilute desiccant solution inside the regenerator thereby heating it extracting away its moisture.

3. Literature survey

Both the solid and liquid desiccant cooling systems, in their various aspects, have been intensively investigated by many researchers. The reported works are related to feasibility studies, performance predictions and evaluations, technology improvement and optimization, and development of new materials and the study of their ageing effects on the desiccant cooling systems performance, etc…

3.1. Feasibility studies

Jain et al. [2] investigated four cycles (the ventilation cycle, the recirculation cycle, the Dunkle cycle and the wet surface heat exchangers cycle) for various outdoor conditions (Dry-bulb temperature and wet-bulb temperature) of many cities in India (see Section 4.1.2 for the different cycles). The study was aimed at evaluating the influence of the effectiveness of heat exchangers and evaporative coolers on the cooling coefficient of performance (COP) as well as on the air volumetric circulation rate in different climatic conditions. The authors found the Dunkle cycle to have better performance compared to recirculation and ventilation cycles in all climatic conditions. But the cycle using wet-surface featured the best performance with respect to all the three other cycles investigated. Mavroudaki et al. [3] and Halliday et al. [4] conducted independently two feasibility studies of solar driven desiccant cooling in diverse European cities representing different climatic zones on the continent. The conclusion reached by the authors revealed

that primary energy savings were achieved in all climatic conditions. A decline in energy savings were noticed in highly humid zones. This decline was attributed to the high temperature required to regenerate the desiccant in the climates of high humidity.

3.2. Performance studies

Alizadeh et al. [5] designed, optimized and constructed a prototype of a forced flow solar collector/Regenerator. They employed an aqueous solution of calcium chloride as desiccant and studied the influence of parameters, such as air and desiccant solution flow-rates as well as the climatic conditions on the regenerator's performance. The performance of a regenerator was measured by the rate at which it removed water vapour from the weak desiccant solution. The conclusion reached in that study was that the performance of the regenerator increased as the air flow-rate increased. The solar collector efficiency generally increased with the increase of the air mass flow-rate. The existence of an optimum value of the air flow-rate at which the efficiency is maximal was also predicted. A strong influence of the solar insolation on the collector/regenerator thermal performance was noticed. Yadav [6] simulated a hybrid desiccant cooling system comprising the traditional vapour compression air conditioning system coupled with a liquid desiccant dehumidifier which was regenerated by solar energy. The study suggested that, when the latent load constitutes 90% of the total cooling load, the system can generate up to 80% of energy savings. Dai et al. [7] conducted a comparative study of a standalone VCS, the desiccant-associated VCS, and the desiccant and evaporative cooling associated VCS. The authors found an increase of cold production by 38.8–76% and that of COP by 20–30%. Mazzei et al. [8] compared the operating costs of the desiccant and traditional systems using the computer simulation tool and predicted operating cost savings of about 35% and a reduction of thermal power up to 52%. In the case were the desiccant would be regenerated by waste heat, the authors projected operating costs savings reaching up to 87%. They also found that cost savings and cooling power reduction increased when the indirect evaporative cooling is used in conjunction with desiccant dehumidification. At this point, it must be pointed out that savings on operating costs are dependent on the local electricity fares, which vary from one country to another, even within the same country. Henning et al. [9] conducted a parametric study of a combined desiccant/chiller solar assisted cooling systems and showed not only their feasibility but also the primary energy savings of up to 50% with a low increased overall costs. Shen et al. [10] used the molecular sieve 13× desiccant wheel as adsorbent in a desiccant cooling system and simulated water vapour and carbon dioxide removal from the process air. The authors conducted an optimisation study involving the coefficient of performance, the temperature of desorption, the overall number of transfer units, and the adsorption time. Techajunta et al. [11] used silica gel as adsorbent and studied its regeneration with simulated solar energy in which incandescent electric bulbs were used to simulate solar irradiation. The regeneration rate was found to be strongly dependent on the solar radiation intensity while its dependence on the air-flow rate was found to be weak. Sanjev et al. [12] studied theoretically and experimentally a liquid desiccant cooling system made of a falling film tubular absorber and a falling film regenerator. For the purpose of performance evaluation, the authors defined wetness factors to characterise the uniformity of wetting of the surface

of the contactors (dehumidifier and regenerator) by the desiccant solution. Their study is of great interest for designing viewpoint, as it can help calculate more accurately the size of the contactors. Kadoma et al. [13] investigated the impact of the desiccant wheel speed, air velocity and regeneration temperature on the COP. The authors showed the existence of an optimal speed and established that the COP decreased when the airflow rate increased and, on the contrary, the temperature of regeneration and the cooling capacity had the same evolution tendency. Shyi-Min et al. [14] reported a standalone solar desiccant enhanced radiant cooling (SDRC), system inherited from the concept of desiccant enhanced nocturnal radiation cooling and dehumidification (DESRAD) [11]. The system is a passive desiccant-cooling scheme operating alternately according to the sequence of diurnal and nocturnal natural cycle. Fathalah et al. [15] studied a heat recovery system. The system studied was a solar energy driven LiBr–H_2O absorption cooling machine. The heat was recovered from the condenser of the machine and added to the driving solar energy. The coefficient of performance was raised 1.2 times, hence 58% higher than that for the absorption machine alone. The evaporator temperature was raised from 11.5 to 19.3 °C. Arshad [16] undertook the study of a mathematical model of a liquid absorber (dehumidifier). The said study has proved the increase of the performance with the number transfer units (NTU) of heat transfer between the process air and the desiccant solution. It is worthy noting here that the NTU is determined, in part, by the size of the absorber. Adam [17] conducted a simulation study on a desiccant cooling system using with aqueous solution of $CaCl_2$ as liquid desiccant. The impact of certain parameters on the system's performance was studied. Those parameters include the desiccant solution's inlet temperature, the space sensible heat ratio (SHR), heat exchanger effectiveness, and the ratio of liquid desiccant flow rate to the air flow rate (G_L/G_a). The authors reached the flowing conclusions:

- The ratio G_L/G_a has been found to have negligible effect on the system performance.
- Increasing the supply inlet temperature of liquid desiccant (up to certain limit) has the effect of improving the system performance for lower values of SHR.
- The system coefficient of performance at given space conditions and inlet temperature of the liquid desiccant increased with the decrease in SHR.
- The system performance decreased with the decrease of the heat exchanger effectiveness.

3.3. Desiccant material studies

The search for desiccant materials with improved sorption capacity has also benefited the attention of researchers. Thus, in Boreskov Institute of Catalysis, in Russia the so-called selective water sorbents for multiple applications were developed. Aristov [43–45] has been the precursor of those hybrid materials developed by impregnating a host porous material (silica gel, vermiculite) with hygroscopic salt (calcium chloride, lithium chloride). The obtained product has a sorption capacity which can triple that of pure host material. Shanghai Jiao Tong University has been contributing to this effort of search for new sorption enhanced materials for several years. Liu et al. [46] developed a composite material obtained by impregnating silica gel with calcium chloride

and obtained a composite adsorbent which was subsequently used to extract water from atmospheric air. William [18] focused on the ageing process of the desiccant materials. They found that desiccant materials subjected to cyclical hydrothermal adsorption/desorption processes deteriorated more rapidly in the early time of its utilisation and the deterioration stabilized afterwards at a negligibly small value during a period of time whose length was dependent on the nature of the desiccant. This period was followed by a more pronounced deterioration tendency which led to the final decay of the desiccant. The degradation in desiccant performance was characterized by the drop in the equilibrium water uptake rate. Alumina and silica gel were found to be ageing more severely after a large number of adsorption/desorption cycles under desorbing temperature of 200 °C. Therefore the authors recommended that their utilisation be limited to the applications with low temperatures of regeneration. The 13× molecular sieve revealed more stability and less severe loss of water adsorption capacity. The most stable among the desiccants tested was, however, the LCIX which was capable of withstanding a large number of adsorption/desorption cycles under a desorption temperature of 250 °C without significant loss of its water vapour equilibrium capacity. Increase in the desiccant wheel speed was also found to minimize the effect of desiccant aging on the system performance. This means clearly that as the desiccant ages, the speed of desiccant wheel must be increased. The study concluded that the slight decrease in adsorbent capacity of adsorption did not affect significantly the overall performance of desiccant cooling systems.

3.4. Use of desiccant cooling for preservation purpose

Besides its use for comfort purpose, the desiccant cooling is used for preservation of products in supermarkets, in warehouses or the preservation of stored cereals. Thorpe et al. [19] developed and tested a desiccant cooling device, regenerated by solar energy employed to preserve stored grains. The device was able to produce a cooling energy up to 50 times the electrical energy input. Dai et al. [20] studied a hybrid system of a rotary dehumidifier wheel and adsorption refrigeration to produce the cooling for preservation of stored grains. The authors predicted an outlet temperature inferior to 20 °C for any given entry conditions (humidity and temperature) as well as a coefficient of performance of the adsorption refrigerator reaching 0.4.

4. Commented examples of desiccant cooling

4.1. Solid desiccant cooling

In the system presented here, desiccant wheel is implemented in association with the evaporative cooling, which can be replaced by a downsized traditional vapour compression air conditioning system.

4.1.1. Evaporative cooling

The evaporative cooling system can be implemented in Indirect Evaporative Cooling mode (IEC) [21,24–40,42] or in Direct Evaporative Cooling mode (DEC) [21,24,37–40].

In the DEC, water is sprayed directly into the process air stream. On the other hand, the indirect evaporative cooling consists in using another air stream cooled directly and evaporatively (called secondary air) as the heat sink to cool the process air (called primary air) inside a heat exchanger, generally a plate heat exchanger (PHE). The DEC is an adiabatic process in which the temperature of process air is lowered only at the expense of higher moisture content in the air (see psychrometric chart at Figs. 3 and 4). This cycle of evaporative cooling can operate efficiently in dry climates. In relatively more humid climates, however, the IEC would rather be the best choice since it enables a real cooling (reduction of enthalpy) without adding moisture into the process air (Figs. 3 and 4). It also allows the use of reduced air volume in comparison with that would be required in direct desiccant cooling.

Fig. 3 shows schematically an example of indirect evaporative cooling. It is composed of several chambers separated by a heat conductor plate. In one chamber, water is sprayed in the secondary air stream which is thus cooled down by a direct evaporative cooling. The primary air is circulated inside the chamber contiguous to the one inside which the cooled secondary air is circulated. Thus, it transmits its heat to the secondary air through the separating plate, realising thus the indirect evaporative cooling. The primary air is used to cool the space and the secondary air is dumped into the environment.

The effectiveness of an evaporative cooler is given by the following relation:

$$\text{Effectiveness} = \frac{\text{Temperature drop}}{\text{Maximum temperature drop}} = \frac{T_{\text{db}} - T_{\text{out}}}{T_{\text{db}} - T_{\text{wb}}} \tag{1}$$

Temperature drop = Dry bulb temperature − Outlet tmperature

Maximum temperature drop = Dry bulb temperature − Wet bulb temperature

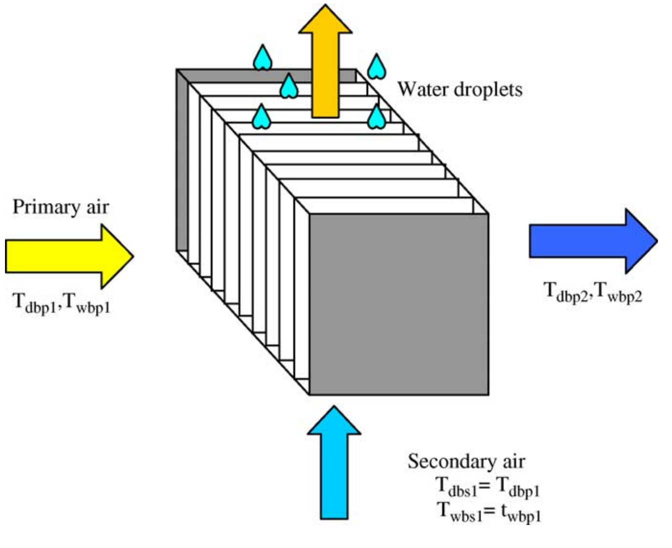


Fig. 3. Indirect evaporative cooling.

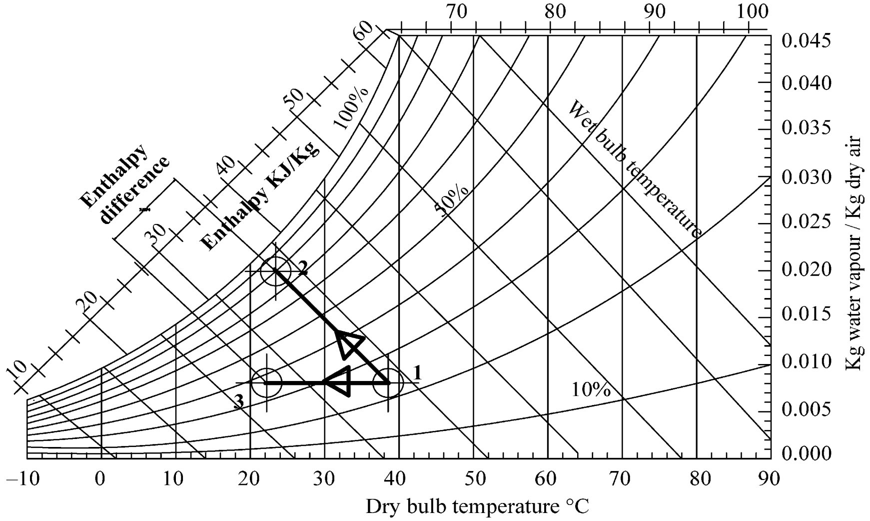


Fig. 4. Psychometric of direct and indirect evaporative cooling.

Where T_{db} is the dry bulb temperature, T_{out} is the outlet temperature, and T_{wb} is the wet bulb temperature.

Since the direct evaporatively cooled secondary air is used to cool indirectly the primary air, the indirect evaporative cooling efficiency would be inferior to that of direct evaporative cooling. The effectiveness of heat transfer from the secondary air to the primary air-which, by no means, can equal 100%-plays a reductive role in the overall process.

In general, evaporative cooling systems are best applied where the ambient wet bulb temperature does not frequently exceed 25 °C [27]. According to Munters [29], they feature an effectiveness of 90% for the DEC and 70–80% for the IEC. They are very effective cooling technologies and have been demonstrated to operate with a COP reaching up to 5 in dry climate [25]. However, in humid climates their effectiveness declines because of already nearly saturation of surrounding air. Therefore, in order to make their utilisation possible in humid climates thereby extending their climatic applicability's scope, resort made to the adjunction of a desiccant dehumidifier, which removes part of moisture of processed air and thus creates the conditions of effective functioning. The scheme thus formed is a desiccant cooling system.

4.1.2. Desiccant aided evaporative cooling

Desiccant cooling systems can be operated in a recirculation mode [26], in ventilation mode [28], Dunkle cycle and wet-surface heat exchanger cycle. In recirculation mode, also called recirculation cycle, the process inlet air is the return air from the space being conditioned and the regeneration air is the outdoor air. In the ventilation mode, the process inlet air is the outdoor air and the regeneration inlet air can be either the outdoor air (standard vent cycle) or the conditioned space exhausted air (Pennington cycle).

The Dunkle cycle, thus named after its inventor, is the recirculation cycle with an additional heat exchanger to improve its performance. The cycles using wet-surface heat

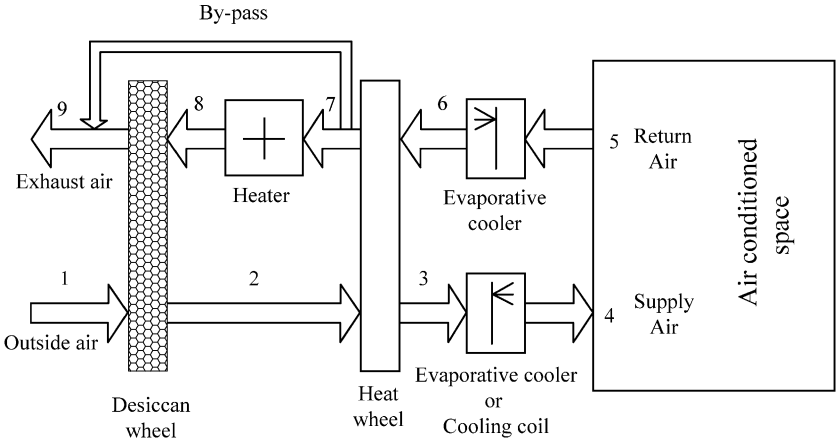


Fig. 5. Desiccant dehumidification associate with evaporative.

exchangers were proposed by Maclaine-Cross and Kang and Maclaine [2]. These cycles employ wet surface instead of evaporative cooler, thus enabling them to obtain a lower dry-bulb temperature of air without increasing humidity level.

The system described here is of the ventilation mode with the regeneration air being the return air form the conditioned space (Pennington cycle).

In the system presented in Fig. 5, the supply outdoor air stream at the state1 is passed through rotary desiccant wheel. Its moisture is partly but significantly adsorbed by the desiccant material and the heat of adsorption elevates its temperature so that a warm and rather dry air stream exits at the state 2. The air stream is then cooled successively in the heat exchanger (heat wheel) from the state 2 to the state 3, and then in an evaporative cooler from the state 3 to the state 4. Another evaporative cooler is used to cool down the return air from the state 5 to the state 6 and the cold air stream serves as heat sink to cool the supply air in the heat exchanger. Consequently, its temperature is risen when exiting the heat wheel at the state 7. At this point, it is ready to undergo a complementary heating to reach a temperature high enough at the state 8 in order to be able to regenerate the desiccant material. A certain portion (about 20%) of the return air stream, at the state 7, bypasses the heating source in order to reduce the regeneration heat consumption.

The performance of the system can be evaluated using the expressions defined below: The Eqs. (2) and (3) give the effectiveness of the evaporative coolers.

$$\varepsilon_{\mathrm{EC1}} = \frac{T_3 - T_4}{T_3 - T_{\mathrm{wb},3}} \tag{2}$$

$$\varepsilon_{\mathrm{EC2}} = \frac{T_5 - T_6}{T_5 - T_{\mathrm{wb},5}} \tag{3}$$

The coefficient of performance of the system is obtained by following relation:

$$\mathrm{COP} = \frac{Q_{\mathrm{cool}}}{Q_{\mathrm{regen}}} = \frac{\dot{m}_{\mathrm{a}}(h_5 - h_4)}{\dot{m}_{\mathrm{a}}(h_8 - h_7)} = \frac{\text{Rate of heat extracted}}{\text{Rate of heat regeneration}} \tag{4}$$

Neglecting the rate of added water vapour with respect to the air flow rate, the mass flow rate of the air can be considered constant. Therefore, the effectiveness of rotary heat wheel can be expressed by

$$\varepsilon_{\mathrm{RHW}} = \frac{T_2 - T_3}{T_2 - T_6} \tag{5}$$

The effectiveness of the desiccant wheel can be expressed by the relation (6).

$$\varepsilon_{\mathrm{DW,1}} = \frac{T_2 - T_1}{T_8 - T_1} \tag{6}$$

The desiccant wheel's effectiveness can also be expressed considering the real performance of desiccant wheel with respect to the regeneration heat input. This second expression of desiccant wheel's effectiveness is given by

$$\varepsilon_{\mathrm{DW,2}} = \frac{(w_1 - w_2)h_{\mathrm{v}}}{h_8 - h_7} \tag{7}$$

where w and h_{v} are the specific humidity and the latent heat of vaporisation of water, respectively.

Another relation giving the performance of the desiccant wheel's effectiveness has been put forward by Van den Bulk et al. [27]. It is

$$\varepsilon_{\mathrm{DW,3}} = \frac{w_1 - w_2}{w_1 - w_{2,\ \mathrm{ideal}}} \tag{8}$$

Where $w_{2,\mathrm{ideal}}$ is the ideal specific humidity of the air stream at the exit of the desiccant wheel. Assuming that the air is completely dehumidified at this point, the value of $w_{2,\ \mathrm{ideal}}$ can be taken as zero.

The rates of moisture added to air by the evaporative coolers in the process and return lines are given by the Eqs. (9) and (10) respectively.

$$\dot{m}_{w1} = \dot{m}_{\mathrm{a}}(w_4 - w_3) \tag{9}$$

$$\dot{m}_{w2} = \dot{m}_{\mathrm{a}}(w_6 - w_5) \tag{10}$$

Where $\dot{m}_{w1}, \dot{m}_{w2}$, are the mass rates at which the air is moistened by the evaporative coolers placed in the supply line and return line, respectively; $\dot{m}_{\mathrm{a}}$ designates the process air mass flow rate.

The evolution of air treatment through the system is represented by the psychometric chart in Fig. 6.

The desiccant-aided evaporative cooling has the following advantages:

- It extends the climatic applicability scope of the evaporative cooling to the hot and humid zones.

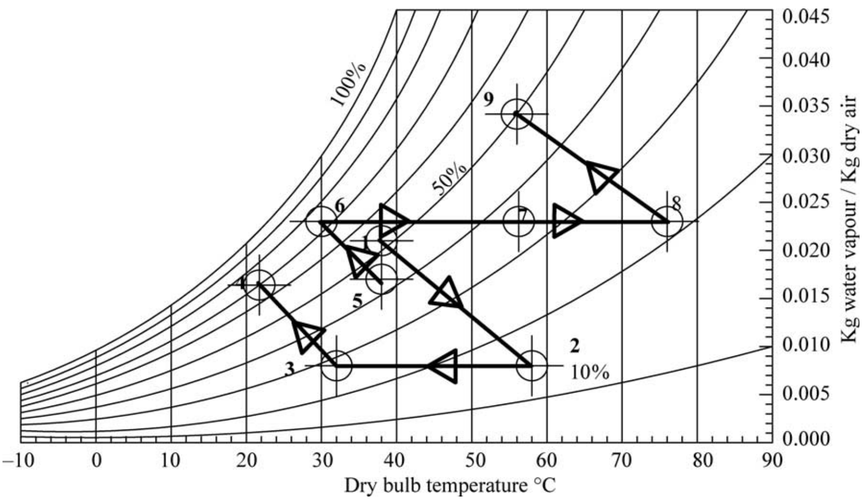


Fig. 6. Psychrometric representation of evaporative cooling aided desiccant cooling.

- The preheating being eliminated, energy and costs can be saved.
- The regeneration heat can be supplied by free energy sources.
- The system is environmental friendly since doesn't use any Chlorofluorocarbon based refrigerant.
- The sensible and latent cooling loads can be handled independently.
- The evaporative cooler can be replaced by the evaporator of a significant downsized traditional air conditioner, depending on the sensible heat ratio (SHR) of the room being conditioned. This will be conducive to significant energy and cost savings.
- The system entails low maintenance cost, since it functions at atmospheric conditions.

4.1.3. Solid desiccant-aided radiant cooling

]The radiant cooling systems were first investigated in laboratory studies in European countries in early 1990s [22]. They are of various types, including metal ceiling panels, chilled beams, and tube embedded ceiling–walls–floors. They have been investigated by many authors [22–23,47–51]. The very idea of space conditioning by thermal radiation is motivated by the desire to decouple the energy transfer mechanisms from the ventilation function while meeting the indoor air quality requirements. This leads to drastic reduction of ventilation air volume. Stetiu [47] showed, in a simulation study, that peak energy savings varying from 27 to 37% can be realised by this decoupling strategy. The radiant cooling systems are expected to feature interesting advantages compared with the vapour compression system. Firstly, an ameliorated comfort is provided to the occupants because of the relative evenly distribution of cooling, avoiding thereby the cold-draft effect. Secondly, the energy needed for a pump to move water is lower than that needed to move air. Moreover, displacement ventilation [22,23] method can be used to eliminate the need for any ventilation fan.

The system constituted by a desiccant wheel and a heat wheel (as described in Section 4.1.2) can be employed advantageously in chilled-ceiling cooling system in hot climates to dehumidifier the incoming air in order to prevent condensation on the ceiling walls and its resulting discomfort. Fig. 7 shows a chilled-ceiling system in which chilled water is circulated in series through the cold coil and the panel embedded in the roof. The incoming air is dehumidified by a desiccant wheel and pre-cooled by heat wheel (the same configuration as in Fig. 6) before been cooled further by the cold coil to the supply temperature. The system has been proposed by Niu et al. [22] and modified by Zhang et al. [23], by adding a heat recovery element (Total Heat exchanger) in order to improve its efficiency. The sensible load is entirely handled by the chilled-ceiling radiant cooler while the latent load is extracted by the desiccant. The use of the desiccant wheel here is of very importance for comfort point of view if this system is to be used in a hot and humid climatic zone. The incoming air is dehumidified by the desiccant thereby preventing unwelcome condensation on the ceiling walls, which would result in discomfort inside the space being conditioned.

The description of desiccant wheel system operation has already been made in Section 4.1.2. The description holds also for this case. The psychrometric evolution (Fig. 8) is different though, due the effect of the interiorly generated cooling by the chilled ceiling.

In addition to the advantages cited above, inherent to chilled-ceiling itself, the adjunction of desiccant can bring about the following advantages:

- The sensible and latent loads are handled independently, the desiccant wheel removing the former while the chilled-ceiling handling the latter, thereby realising the so-called decoupled cooling [23].

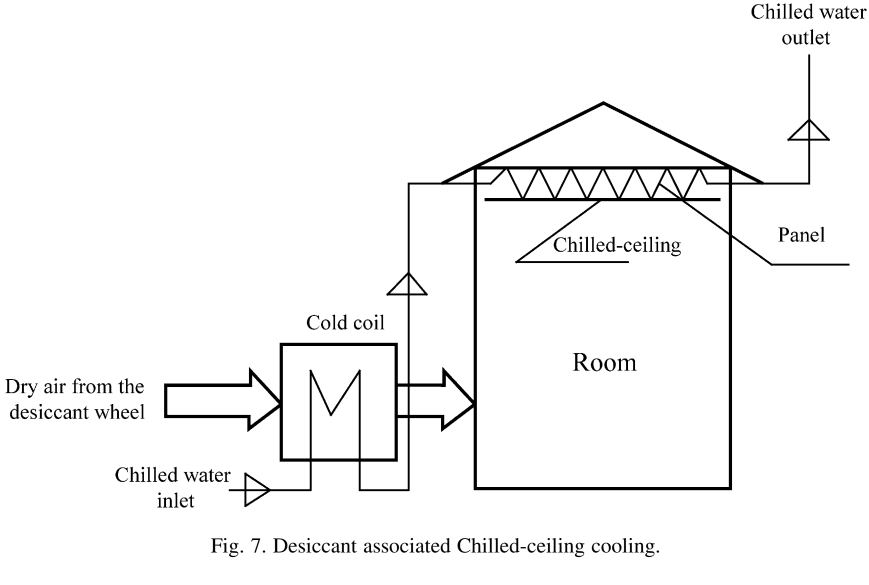


Fig. 7. Desiccant associated Chilled-ceiling cooling.

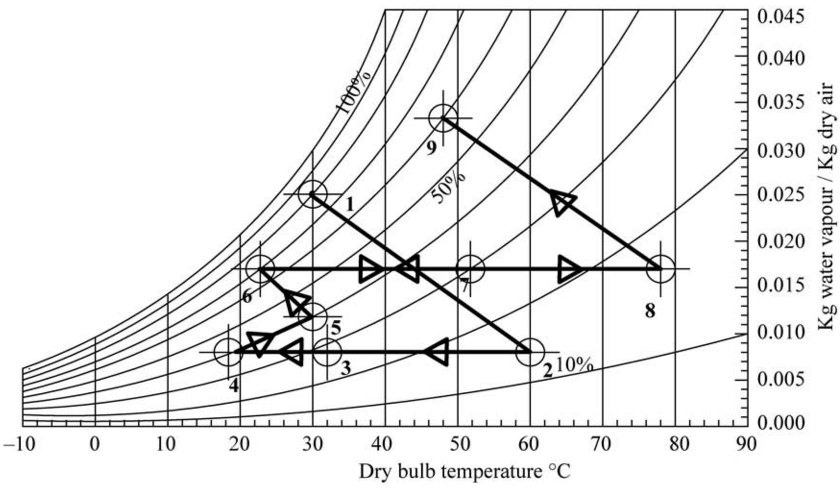


Fig. 8. Air psychrometric evolution in chilled-ceiling desiccant cooling.

- The absence of reheating allows great energy saving, the authors of Ref. [22] suggested some 44% of primary energy savings in comparison with the vapour compression traditional all-air system.
- A single water chiller is used since water is circulated in series in the cold coil and the cooling panel. The temperature of chilled water can be as high as 17 °C, which will entail an increase in the chller's coefficient of performance.
- The system can be driven by low grade energy, especially the free energy such as solar energy and waste heat.
- The system delivers a draft and noise free conditioned air.

4.2. Liquid desiccant cooling

The liquid desiccants are attractive because of their operational flexibility and their capability of absorbing pollutants and bacteria [31]. Compared to the solid desiccants, they are generally regenerated at relatively lower temperature [41] and, equally cause lower airside pressure drops. Their disadvantage is their carryover in the process air stream during the dehumidification operation. Technologically, the equipment providing air/solution contact surface (contactor) can be a wetted wall/falling film [12,30,32,35] absorber, a spray chamber [29,38] or a packed tower [33]. The packed towers are subdivided into regular [34] (structured) or irregular (random) packing modes.

The liquid desiccant assisted air conditioning can achieve up to 40% of energy savings with regard to traditional air conditioning system [33] and those savings become even greater when the calorific energy needed for regeneration is drawn from waste heat, solar energy or any other free energy sources.

The earliest liquid desiccant was suggested by Lof [32] with the Triethylene Glycol (TEG) used as desiccant that was regenerated by solar heated air current. Potlis et al. [30] and Löf et al. [36] both studied the mass transfer in the randomly and structured arranged

humidifier as well as in the regenerator and found that the mass transfer resistance in the gas phase was negligible compared the liquid phase mass transfer resistance. Ali et al. [33] also conducted similar study but on an inclined dehumidifier. The results yielded were significant in the sense that they showed that the inclination angle played a significant role in improving dehumidification and the cooling processes of liquid desiccant for both inclined parallel and counter flow channels.

The performance of desiccant cooling system can be evaluated using the hereafter mathematical expressions. These expressions were derived by the authors of Ref. [27]. The air moisture removal effectiveness is defined by

$$\varepsilon_{\mathrm{m}} = \frac{p_{\mathrm{a,i}} - p_{\mathrm{a,o}}}{p_{\mathrm{a,i}} - p_{\mathrm{s,i}}} \tag{11}$$

Where $P_{\mathrm{a,i}}$, $P_{\mathrm{a,o}}$, $P_{\mathrm{s,i}}$, designate respectively the air inlet water vapour pressure, air outlet water vapour pressure, and the solution vapour pressure.

Likewise, the dimensionless temperature ration is defined by

$$\varepsilon_{\mathrm{HE}} = \frac{T_{\mathrm{s,o}} - T_{\mathrm{s,i}}}{T_{\mathrm{s,o}} - T_{\mathrm{c,i}}} \tag{12}$$

Where $T_{\mathrm{s,o}}$, $T_{\mathrm{s,i}}$, $T_{\mathrm{c,i}}$, designate, respectively, the desiccant solution outlet temperature, the desiccant solution inlet temperature, the cooling medium inlet temperature.

The outlet temperature of the desiccant solution is derived from the expression (12) and represented by the expression (13).

$$T_{\mathrm{s,o}} = \frac{T_{\mathrm{s,i}} - \varepsilon_{\mathrm{HE}} T_{\mathrm{c,i}}}{1 - \varepsilon_{\mathrm{HE}}} \tag{13}$$

The relation linking the concentrations of inlet and outlet desiccant solution is given by

$$\frac{1}{\xi_{\mathrm{o}}} = \frac{1}{\xi_{\mathrm{i}}} \left(1 + \frac{\dot{m}}{G_{\mathrm{i}}}\right) \tag{14}$$

Finally the mass rate of moisture removal is obtained as

$$\dot{m} = \frac{1}{L} \left[\frac{C_{\mathrm{s}} \varepsilon_{\mathrm{HE}}}{(1 - \varepsilon_{\mathrm{HE}})} (T_{\mathrm{s,i}} - T_{\mathrm{c,i}}) - C_{\mathrm{a}} \beta (T_{\mathrm{a,i}} - T_{\mathrm{s,i}}) \right] \tag{15}$$

Where C_{s} and C_{a} designate the heat capacities of the solution and the air, respectively, L designates the latent heat of condensation of water.

4.2.1. Vapour compression air conditioning aided liquid desiccant cooling system

An example of desiccant cooling application is represented in Fig. 9. Here, the cool strong desiccant solution is sprayed onto the top of the dehumidifier through spraying nozzles. By gravitation, it trickles through the structure of the dehumidifier where it gets contact with the process air stream blown perpendicularly to its trickling flow direction. Since, the cool and strong desiccant solution vapour pressure is less than that of the air vapour pressure [17], water vapour migrates from the air stream to the desiccant solution and condenses therein. Consequently, the heat of condensation and mixing are liberated

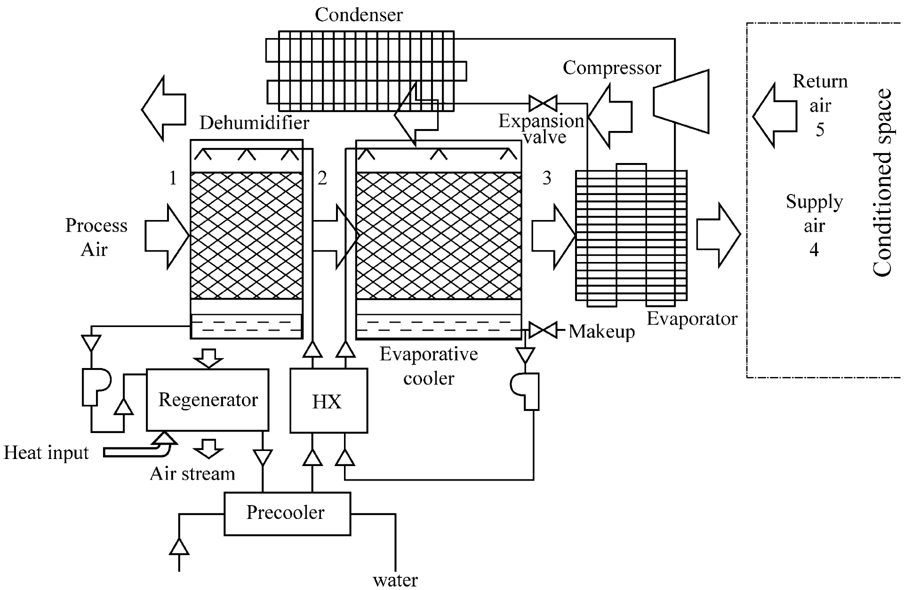


Fig. 9. Schematic of liquid desiccant aided vapour compression air conditioning.

causing an increase in the solution's temperature. The process air stream is slightly cooled down due to its contact with the cold desiccant solution. The dehumidified and rather warm process air stream then passes successively through the evaporative cooler and the evaporator of the traditional refrigerant vapour compression air conditioner, before been delivered into the conditioned space. The diluted desiccant solution, exited from dehumidifier, is circulated through the regenerator where it is heated and the moisture absorbed in the dehumidifier is now lost to the scavenger air stream. In order for the system to keep functioning continuously and effectively, an equal amount of water vapour absorbed from the humid air and condensed to the desiccant solution in dehumidifier must be evaporated from the desiccant solution in the regenerator. The hot and strong desiccant solution is thereafter cooled down in the pre-cooler and then cooled further in the heat exchanger (HX) before being ready again to dehumidify the incoming process air.

The lowest limit temperature attainable by the evaporative cooler is the process air wet bulb temperature which decreases with the decrease of the relative humidity and increases with the elevation of the dry bulb temperature. The essential role of the desiccant solution in this example is to lower the relative humidity of the incoming air stream in order to enable the evaporative cooler to function more effectively.

Here, the desiccant assisted evaporative cooling is associated with the traditional vapour compression air conditioning to reduce its size and enhance its coefficient of performance. Because the latent load is handled independently by the desiccant dehumidifier, the need of cooling the ventilation air below its dew point is obviated. The temperature of evaporation can thus be lifted up to 15 °C from its generally practiced level of 5 °C for the traditional vapour compression system. The increase in evaporation temperature will entail the increase of the system's coefficient of performance (COP).

This assemblage can be useful in humid climates where the wet bulb temperature is fairly high. In such climates, a significantly downsized vapour compression air conditioner can be supplemented with a desiccant assisted evaporative cooler in order to reach the desired indoor temperature, thus enabling costs and energy savings and improving the indoor air quality.

4.2.2. Evaporative cooling complemented with desiccant

Besides, their use to enhance the efficiency of the traditional vapour compression system (Section 4.2.1), liquid desiccants can be also used in conjunction with the evaporative cooling systems to form standalone applications. An example thereof is presented in Fig. 10. It has been proposed by Saman et al. [39,40]. It is a counter-flow type plate heat exchanger (PHE) made of several passages separated from each other by thin plastic plates. Each thin plate, besides separating the water–air passage from the solution–air passage, also provides a contact area for heat and mass transfer between the fluids flowing in each passage. Two consecutive passages separated by a thin plate form a chamber. On one side of the separating plate water is brought in contact with the secondary air which is thereby cooled by a direct evaporative cooling. This cooled secondary absorbs heat from the primary air on the other side of the plate thus realising the indirect evaporative cooling. This primary air stream is concurrently dehumidified through a cross-flow contact with the desiccant solution sprayed using nozzles.

The authors first studied theoretically its hydrothermal performance by the means of mathematical modelling and numerical simulation. In a second work, they then tested its performances and compared them to the theoretically predicted values. The tests were carried out under the tropical climatic conditions in Brisbane, Australia. The parameters used to study the performance are, among others, the primary air inlet humidity ratio, the primary air inlet temperature, the primary air inlet mass flow rate, and the heat exchanger angle. The heat exchanger angle designates the angle between the direction of water spray nozzle and the vertical or, between the direction of

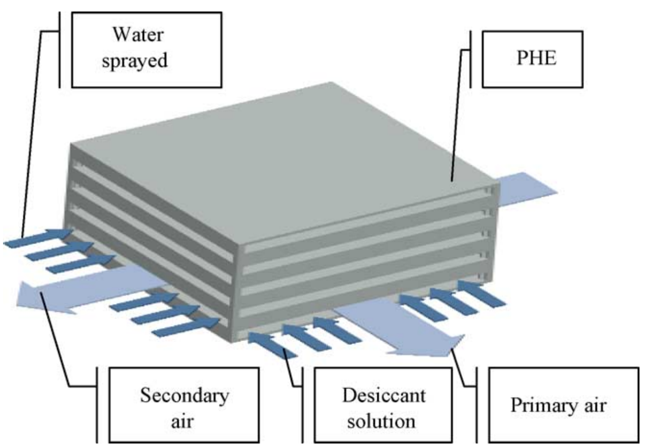


Fig. 10. Compact heat exchanger–dehumidifier.

desiccant spraying direction and the horizontal. The return air from the conditioned space was used as secondary air to improve the secondary side performance, since it is usually drier than the outside air.

It was found notably that for the exchanger angle of 45°, the effectiveness of evaporative cooling could reach 75%, which is a good effectiveness value for an indirect evaporative cooling application. It has also shown that, depending on the primary air flow rate, the system could reach a good efficiency of humidity removal as well.

This system possesses a certain number of advantages. Firstly, it employs liquid desiccant which is regenerated at a temperature relatively lower than the solid desiccant, so solar energy and waste heat can readily be used to drive it. Secondly it is compact and another stage of evaporative cooler can be added to it in order to reach even lower indoor temperature. Thirdly the technology used is not sophisticated at all, therefore it can be easily applied in the regions having abundant solar energy resource and therefore serious cooling needs but lacking technological expertise.

5. Conclusion

Throughout this review, it has been seen that the desiccant cooling is a simple technology which can be joined to other technologies to improve their efficiency. Evaporative and radiant ceiling cooling for instance, are not effective in climates where the wet-bulb temperature is high. Desiccant cooling can supplement them advantageously by extending their climatic applicability's scope. Its potential contribution in improving indoor air quality, costs and energy savings, as well as environmental protection makes it attractive at a time where depletion of energy resources and environmental degradation are worldwide concerns. Although the desiccant cooling has its penalty which is the energy required to reactivate (regenerate) the desiccant, it has been seen throughout this literature review that, in overall, energy saving potential is significant. This potential is mainly due to the elimination of the overcooling and the reheating. One of most important advantages of desiccant cooling systems undoubtedly lies in the possibility of their regeneration by the free energy such as waste and solar without any beforehand conversion. Amelioration of indoor air quality brought about by its ability of removing pollutants and contaminants and its environmental friendly nature make the desiccant cooling an appropriate and timely technology.

The research of desiccant materials that can be regenerated under lower temperature, (near-ambient) is the key of augmenting even greater the contribution that the desiccant cooling can bring to the amelioration of comfort, energy and cost savings.

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